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# Aerodynamic/Stealthy/Structural Multidisciplinary Design Optimization of Unmanned Combat Air Vehicle

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## Abstract

An optimization strategy is proposed to deal with the aerodynamic/stealthy/structural multidisciplinary design optimization (MDO) issue of unmanned combat air vehicle (UCAV). In applying the strategy, the MDO process is divided into two levels, i.e. system level optimization and subsystem level optimization. The system level optimization is to achieve optimized system objective (or multi-objective) through the adjustment of global external configuration design variables. The subsystem level optimization consists of the aerodynamic/stealthy integrated design and the structural optimization. The aerodynamic/stealthy integrated design aims at achieving the minimum aerodynamic drag coefficient under the constraint of stealthy requirement through the adjustment of local external configuration design variables. The structural optimization is to minimize the structural weight by adjusting the dimensions of structural components. A flowchart to implement this strategy is presented. The MDO for a flying-wing configuration of UCAV is employed to illustrate the detailed process of the optimization. The results indicate that the overall process of the surrogate-based two-level optimization strategy can be implemented automatically, and quite reasonable results are obtained.

**Keywords:** aircraft design; multidisciplinary design optimization; aerodynamics; radar cross section; structure

## 1. Introduction

Modern unmanned combat air vehicles (UCAVs) are expected to meet various demanding requirements such as high lift-to-drag ratio, low radar cross section (RCS), and light structural weight. During the UCAV conceptual or preliminary design phase, how to obtain an optimum design in terms of aerodynamics, stealth, and structure is of greatest concern for designers. Multidisciplinary design optimization (MDO) has been proved to be a promising method to solve this kind of problem<sup>[1]</sup>, which has been applied to aerodynamic/structural design optimization<sup>[2-3]</sup> and aerodynamic/stealthy integrated design optimization<sup>[4-6]</sup>. To the best of our knowledge, very few published articles have been focused on the issue of aerodynamic/stealthy/structural integrated design optimization<sup>[7]</sup>. The aim of this article is to propose a systematical method to deal with the aerodynamic/stealthy/structural MDO issue for the UCAV.

## 2. UCAV Optimization

A UCAV with flying-wing configuration (see Fig.1), which is similar to the UCAV configuration shown in Ref.[8], is used as a specific example. The UCAV is expected to be designed so that it has low aerodynamic drag, low RCS, light structural weight, and enough internal space.

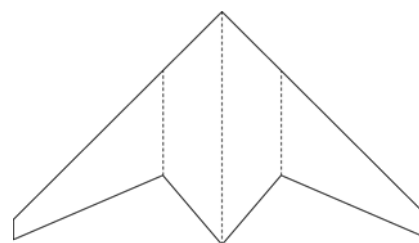


Fig.1 General UCAV configuration.

In terms of optimization, this UCAV design problem can be briefly formulated as follows. More detailed definitions will be found in Section 4.

**Objectives** ① Minimized aerodynamic drag; ② Minimized structural weight.

**Design variables** ① Parameters for describing the external configuration of UCAV; ② Parameters for describing the structure of UCAV.

**Constraints** ① Aerodynamic requirements; ②

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RCS requirements; ③ Structural requirements; ④ Internal volume for holding fuel and weapons.

The above-mentioned design optimization problem is very complex and difficult to be solved by the traditional optimization methods, because it involves several disciplines (aerodynamics, stealth, and structure) and has a large number of design variables and constraints. Hence, an effective strategy of MDO is needed.

### 3. Optimization Strategy

The experiences of utilizing the MDO methods have revealed that the multi-level optimization and surrogate modeling are effective approaches to solve the complex design problems<sup>[1]</sup>. To conduct the aerodynamic/stealthy/structural MDO of UCAV, an optimization strategy, which is referred to as surrogate-based two-level optimization, is proposed and presented in the following subsections.

#### 3.1. Two-level optimization strategy

The basic idea of the two-level optimization strategy is depicted in Fig.2.

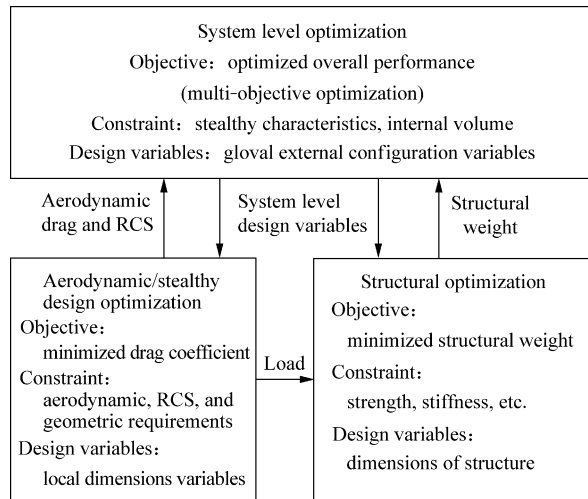


Fig.2 Two-level optimization strategy for aerodynamic/stealthy/structural integrated design.

The optimization process is divided into two levels, i.e. the system level optimization and the subsystem level optimization.

In the system level, the variables that have large effects on the aerodynamic drag, RCS, and structural weight are taken as the system level variables. The objective of the system level optimization is to achieve the optimized overall performance (i.e. minimum aerodynamic drag and structural weight) through the adjustment of the system level design variables and meanwhile satisfy the requirements of RCS and internal volume.

One of the subsystem optimizations is aerodynamic/stealthy design optimization. Its objective is to achieve the minimum drag coefficient under the constraints of aerodynamic characteristics (such as lift

coefficient and pitching moment coefficient), RCS, and geometric dimensions (thickness of airfoils) through the adjustment of local external configuration design variables. The local external configuration variables are the design variables that have large effects on aerodynamic characteristics and RCS, but few effects on structural design. Another subsystem optimization is structural optimization, the objective of which is to achieve the minimum structural weight under the constraints of the material allowable stress and structural deformation through the adjustment of structural dimensions.

The final result can be found by the iteration of the system level and the subsystem level optimizations until converging to the optimum values.

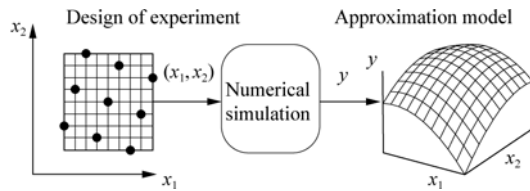
This strategy of two-level optimization makes the optimization process (both for system and subsystem optimization) be more easily being tackled since the design variables and constraints are considerably lesser than that of the original optimization process. Another advantage of this strategy is that the subsystem optimization is an automatically selecting optimization algorithm and disciplinary analysis model so that the existing programs or software of each discipline can be fully used. The disadvantage of this two-level optimization strategy may be that a large amount of subsystem optimization effort is needed, consequently causing high computational expense. This problem can be overcome by using surrogate modeling.

#### 3.2. Surrogate modeling

The concept of surrogate modeling is to construct a simplified mathematical approximation of the computationally expensive simulation and analysis code, which is then used to take the place of the original code to facilitate the MDO and design space exploration. Since this model acts as a surrogate for the original code, it is often referred to as surrogate model<sup>[9]</sup>.

The construction of surrogate model consists of three steps as shown in Fig.3<sup>[10]</sup>: ① a design of experiment is used to generate sample points in the design space to define the sample designs; ② the numerical simulation is performed to obtain the performance (output) of each design defined by sample points; ③ the sample data (input/output data) are fitted by an approximation method to construct the surrogate model. Once the surrogate model is constructed, it must be validated in order to ensure that it is sufficiently accurate to be used as a surrogate for the original code.

There are two kinds of approaches to generate sample points<sup>[11]</sup>, i.e. experimental design method and computer experimental design/analysis method. Experimental design method originates from the experimental sampling methods, such as full factorial design, central composite design, etc. However, recently it is believed that computer experimental design/analysis method is more suitable for being used as sampling

Fig.3 Construction of surrogate model<sup>[10]</sup>.

method for numerical simulation. The Latin hypercube and the uniform design methods are two examples of this kind of method. The most widely used approximation methods are polynomial response surface model method, artificial neural network method, kriging model method, radial basis function method, etc<sup>[12]</sup>.

### 3.3. Surrogate-based two-level optimization

In this article, the surrogate model acts as a surrogate for the subsystem optimization to overcome the high computational expense problem of the two-level optimization. The combination of two-level optimization strategy and surrogate model results in a MDO strategy, which is referred to as the surrogate-based two-level optimization and is depicted in Fig.4.

Once the surrogate models for the subsystem optimizations are constructed, they will serve as the analysis models for the system optimization. Since the surrogate models are very cheap to run, all kinds of optimization algorithm including multi-objective genetic algorithm can be used to search the optimal design without suffering from high computational expense. The strategy of the surrogate-based two-level optimization can not only reduce computational ex-

pense, but also facilitate implementing parallel computation. This is because all sample points of the design space at the system level can be carried out independently and simultaneously in the cluster computer environment.

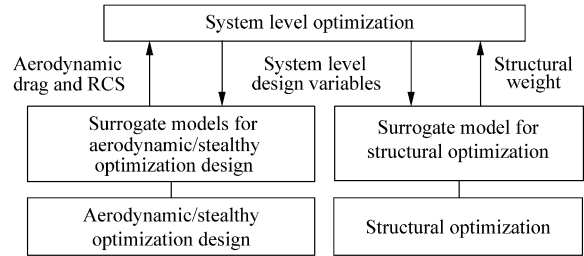


Fig.4 A framework of surrogate-based two-level optimization.

## 4. Implementation Procedure

Following the framework of surrogate-based two-level optimization, a more detailed procedure for solving the UCAV aerodynamic/stealthy/structural integrated design optimization problem is presented in the flowchart as depicted in Fig.5. To implement this procedure, some key enabling techniques such as parametric geometry definition, automatic generation of analysis models for aerodynamics, RCS, and structure are essential. The overall procedure will be explained step by step in the following subsections.

### 4.1. Parametric geometry definition

The flying-wing configuration of UCAV is shown in Fig.6. Basically, this configuration consists of the inner

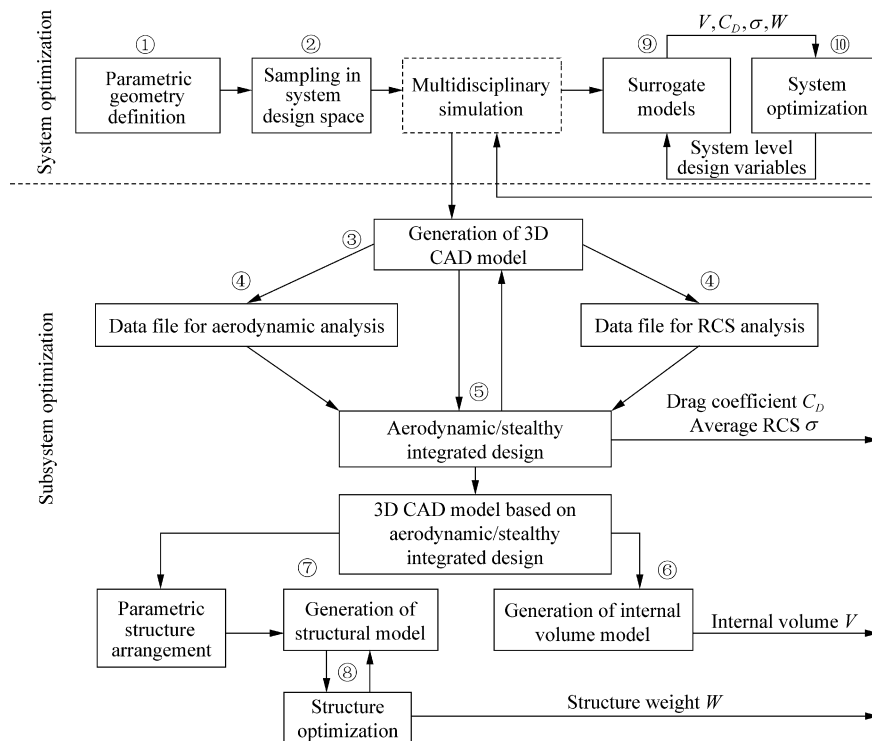


Fig.5 Flowchart of aerodynamic/stealthy/structural multidisciplinary design optimization.

wing and outer wing. The parameters defining this configuration can be grouped into three sets.

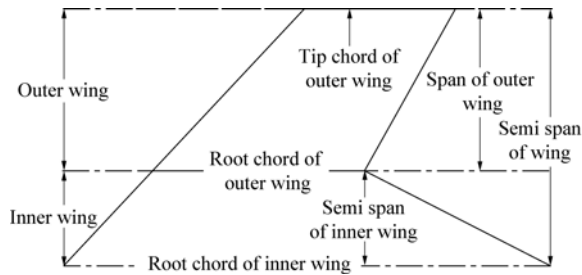


Fig.6 Flying-wing configuration platform.

#### (1) Parameters for wing outline

These parameters are used to describe the plane shape, torsion angle and dihedral angle of wing, including root chord length of inner wing, semi span of inner wing, swept angle of wing, taper ratio of inner wing, taper ratio of outer wing, torsion angle of outer wing, torsion angle at wing tip, dihedral angle, and span of outer wing. All the other outline parameters can be derived from the above mentioned parameters.

#### (2) Parameters for master sections

Master sections are referred to as the typical sections of flying-wing along the streamline of airflow. Other sections can be fitted by these master sections. For example, the sections at inner wing root, outer wing root, and outer wing tip can be regarded as master sections. The parameters describing the profile of master sections are called the parameters for master sections. The parametric models for master sections are constructed using an approach based on shape function and classification function<sup>[13]</sup>. This approach has clear physical meaning, and provides an easy way to control the section profile.

#### (3) Parameters for transitional surfaces

The transitional surfaces are referred to as the surfaces smoothly connecting the root section of outer wing and the root section of inner wing. The shape of the transitional surface can be controlled by a set of parameters, which are called the parameters for transitional surfaces control. This article adopts the guidelines to generate transitional surfaces. The guidelines are the boundary lines for lofting between the master sections. The key to generate the transitional surfaces is to define a set of guidelines. The spatial cubic Hermite curves<sup>[14]</sup> are used to define the shape of guidelines. Usually, two parameters are required to define a spatial cubic Hermite curve. In this article, four spatial cubic Hermite curves are used to describe the transitional shape of the UCAV. Hence, eight parameters are needed for the definition of the transitional surfaces.

During optimization, four parameters of spatial cubic Hermite curves are selected as system level design variables and the other parameters are fixed.

The detail of the parametric model for the flying-wing configuration can be found in Ref.[14].

### 4.2. Sampling in system design space

Some parameters mentioned above will be selected as the system level design variables if they have considerable effects on all the aerodynamic, stealthy, and structural characteristics. Since the swept angle of wing, span of outer wing, and parameters of transitional surfaces (totally six parameters) have large effects on aerodynamic/stealthy/structural characteristics, these six parameters are selected as the system level design variables. Other parameters are considered as the local design parameters for external configuration or fixed parameters.

The Latin Hypercube method is used to generate the sample points for the system level design variables. The number of initial sample points is 100. If the accuracy of the surrogate model does not reach the expected level for the validation, the additional design samples are needed to improve the accuracy. 20 design samples are randomly selected to verify the accuracy of the surrogate model. If the relative error of the surrogate model is not less than 5%, these 20 random design samples will be added to the initial sample database to update the surrogate model. This process is iterated until the accuracy of the surrogate model is satisfied. For this UCAV problem, five times of iteration are needed, which means 100 additional design samples are added to the initial sample database. This results in 200 design samples in total.

### 4.3. Generating 3D CAD model

A geometric model generator of computer graphics aided three dimensional interactive application (CA-TIA) for the UCAV configuration is developed by the Microsoft Visual Basic (VB) routine. This is implemented by recording and modifying the macro commands of CATIA during constructing the 3D parametric CAD model of UCAV. For details, see Ref.[14]. With this VB routine, 3D CAD models for different UCAVs can be automatically generated, given the parameters of UCAV configuration. An example of the UCAV configuration generated by the geometric model generator is shown in Fig.7.



Fig.7 A generated flying-wing 3D CAD model.

### 4.4. Generating aerodynamic and RCS models

A numerical code (FLO22)<sup>[15]</sup>, which is based on the transonic full potential equation, is adopted for aerodynamic analysis. Grid can be automatically generated in this code. Lift coefficient, pitching moment coefficient, induced drag coefficient, and wave drag coefficient are computed by FLO22. Friction drag coefficient

cient is computed by the boundary layer theory.

A Fortran program RCS-panel, which is developed using the physical optics and the equivalent current methods<sup>[16]</sup>, is used to predict the RCS of the UCAV.

The aerodynamic analysis and RCS computation require the surface mesh information of the UCAV configuration, such as the coordinates of mesh nodes and panel numbers, as shown in Fig.8. A model generator for aerodynamic and RCS analyses is developed to generate and extract the coordinates of mesh nodes through the following steps: ① the 3D CAD model is transmitted into the software Gridgen for surface mesh generation; ② the nodes on each master sections are distributively arranged; ③ the data file for the mesh nodes generated by Gridgen is saved; ④ the data format of the saved file is converted to the data format suitable for aerodynamic and RCS analyses.

Once the data files for aerodynamic and RCS analyses are generated, the aerodynamic characteristics and RCS for the given UCAV geometric model can be predicted straightforwardly by executing the FLO22 code and the RCS-panel program.

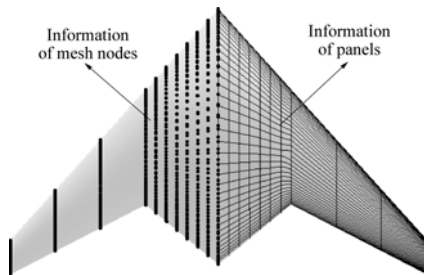


Fig.8 Geometric data for aerodynamic and RCS analyses.

#### 4.5. Aerodynamic/Stealthy integrated design

In terms of optimization, the aerodynamic/stealthy integrated design can be stated as follows:

**Given conditions** Flight Mach number is 0.8, flight altitude is 11 km, radar threat sectors:  $0^\circ$ - $30^\circ$  and  $60^\circ$ - $120^\circ$  (measuring from the nose of the UCAV).

**Given parameters** The values of system level design variables are based on sample points.

**Objective** Minimized aerodynamic drag coefficient  $C_D$ .

**Design variables** The parameters for master sections, torsion angle of outer wing, torsion angle at the wing tip, and angle of attack, totally nine design variables.

**Constraints** ① Design lift coefficient,  $C_L \geq 0.14$ ; ② Pitching moment coefficient at 1/4 chord,  $-0.08 \leq C_M \leq 0$ ; ③ The average RCS within the threat sector of radar,  $\sigma \leq -14.6$  dBsm; ④ The thickness of master sections at front spar and rear spar.

The sequential quadratic programming is adopted to solve the aerodynamic/stealthy integrated design problem.

Since the design lift coefficient is constrained in the optimization process, the minimization of drag coefficient

is equivalent to the maximization of lift-to-drag ratio.

#### 4.6. Generating internal volume model

The volume of inner wing box is required to be computed in order to account for the constraint of internal volume. A VB-CATIA script is developed to implement the process for generating inner wing box model (see Fig.9). The process of the volume computation is as follows: ① the position of inner wing box is located; ② the auxiliary planes are used to separate the inner wing box; ③ the volume of the inner wing box is computed using the function of volume computation of CATIA.

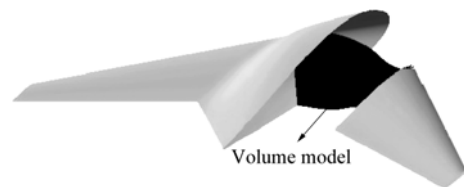


Fig.9 Internal volume model based on CATIA.

#### 4.7. Generating structural model

The purpose of this section is to generate the structural layout and finite element models based on the 3D geometric model of UCAV.

The structural layout of UCAV is depicted in Fig.10. The features of the structural layout are defined by the number of spars, the positions of the spars, the number of ribs, and the orientation of the ribs. For this UCAV, the number of spars is three, i.e. front spar, middle spar, and rear spar; the three spars are located at 16%, 39%, and 62% of the local chord of wing, respectively, and the number of ribs is 17, which are vertical to the front spar. The initial dimensions of the elements (skin thicknesses, areas of the spar caps, areas of the rib caps, etc.) are assigned by the rational guess. The material of the structure is aluminum alloy.

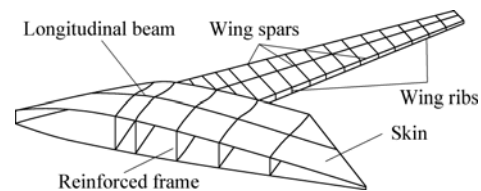


Fig.10 Structural layout of UCAV.

Once the layout and initial dimensions of the structure are defined, a structural analysis model generator, which is a computer program using the VB-CATIA script and Patran Command Language, is used to generate the finite element model for the UCAV structure, as shown in Fig.11. In the finite element model of the structure, the skins and webs of spars, ribs, and reinforced frames are modeled by plates, and the spars and the stiffeners for webs are modeled by rods.

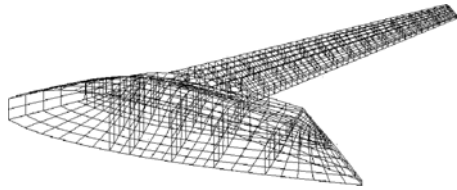


Fig.11 Finite element model for UCAV structure.

#### 4.8. Structural optimization

After the finite element model of UCAV structure is generated, the structural optimization can be carried out. The task of the structure optimization is to find the dimensions of structural elements with minimum structural weight under the constraints of the material allowable stress, structural deformation, and geometry dimensions. The formulation of the structural optimization problem is as follows:

**Objective** Minimized structural weight  $W$ .

**Design variables** ① The areas of spar caps, ribs, and reinforced frames; ② The thicknesses of the webs of spars, ribs, and reinforced frames; ③ The thicknesses of wing skins; ④ The stiffener areas of the webs.

**Constraints** ① The axial stress of the rods  $\leq 450$  MPa; ② The shear stress of the plates  $\leq 250$  MPa; ③ The displacement of wing tip  $\leq 5\%$  of the semi span of wing.

The sequential quadratic programming, which is provided by MSC Nastran software, is adopted to solve the structural optimization problem.

#### 4.9. Construction of surrogate models

The surrogate models for the UCAV analysis at system level can be constructed by using the sample points of system level design variables (see Section 4.2) and their corresponding results. These results include the aerodynamic drag coefficient and RCS resulted from aerodynamic/stealthy integrated design (see Section 4.5), the internal volume computation results (see Section 4.6), and the structural weight resulted from structural optimization (see Section 4.8). Concerning the selection of surrogate models, our experience indicates that the Kriging model is suitable for constructing the surrogate models to predict the drag coefficient, RCS, and structural weight, while the quadratic response surface model is suitable to construct the surrogate model of the internal volume.

#### 4.10. System optimization

The system optimization can be conducted once the surrogate models for UCAV analysis are constructed. The task of the system optimization is to find the optimum configuration which has the desired characteristics in terms of aerodynamics, stealth, and structure. The system level optimization is formulated as follows:

**Objectives** ① Minimized aerodynamic drag coefficient  $C_D$ ; ② Minimized structural weight  $W$ .

**Design variables** There are six system level design variables, including the swept angle of wing, span of outer wing, and four parameters for transitional surface.

**Constraints** ① The average RCS within the threat sector of radar,  $\sigma \leq -14.6$  dBsm; ② The wing box volume,  $V \geq 5.5$  m<sup>3</sup>.

This system optimization is a multi-objective optimization problem. A multi-objective genetic algorithm, namely NSGA-II<sup>[17]</sup> is selected to solve this multi-objective optimization problem. Since the surrogate model for the UCAV analysis is very cheap in terms of computing expense, the use of NSGA-II will not encounter the problem of computing expense.

#### 4.11. Optimization results

All the steps (Sections 4.1-4.10) are integrated into the software iSIGHT<sup>[18]</sup>. The overall process of the multidisciplinary design optimization is executed automatically.

Pareto optimal solution set obtained from system level optimization is shown in Fig.12.

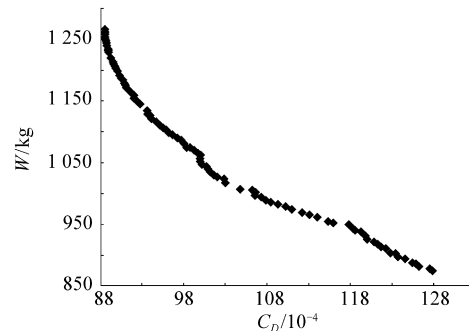


Fig.12 Pareto optimal solution set obtained from system level optimization.

One can select an optimal point from the Pareto optimal solution set. If an optimal point with lower structural weight and higher drag coefficient is selected, the corresponding design is a design with the smaller swept angle and shorter span of outer wing. If an optimal point with higher structural weight and lower drag coefficient is selected, the corresponding design is a design with the larger swept angle and longer span of outer wing.

Three typical subsets of Pareto optimal solution set are listed in Table 1. The subset *A* is a set of optimization results with better aerodynamic performance. The subset *C* is a set of optimization results with lighter structural weight. The subset *B* lies between *A* and *C* with both relatively better aerodynamic performance and lighter structural weight. For example, design 1 in Table 1 is the best design in terms of aerodynamic performance; design 15 is the best one in terms of structural weight; and design 8 is the design with both the compromised aerodynamic performance and structural

weight. If design 8 is selected, the aerodynamic drag coefficient  $C_D$  will be decreased by 19.76%, the structural weight  $W$  will be reduced by 39.4%, and the average RCS within the threat sector of radar will be less than  $-14.03$  dBsm compared to the initial design with  $C_D = 0.01186$ ,  $W = 1834.62$  kg, and  $\sigma = -14.03$  dBsm.

**Table 1** Typical solutions in Pareto optimal solution set

	No. of design	Objective function		Constraint
		$C_D$	$W/\text{kg}$	$\sigma/\text{dBsm}$
A	1	0.008 852	1 266.709	-15.543 9
	2	0.008 901	1 229.162	-15.434 1
	3	0.009 003	1 198.659	-15.378 8
	4	0.009 109	1 173.031	-15.313 7
	5	0.009 205	1 155.236	-15.164 8
B	6	0.009 365	1 133.865	-15.217 1
	7	0.009 408	1 122.464	-14.645 6
	8	0.009 517	1 110.541	-14.667 7
	9	0.009 617	1 099.616	-14.796 6
	10	0.009 728	1 090.988	-14.893 1
C	11	0.009 812	1 079.521	-14.607 6
	12	0.009 924	1 071.117	-14.717 9
	13	0.010 071	1 044.901	-15.238 2
	14	0.011 027	979.029	-14.649 7
	15	0.012 782	876.829	-14.601 1

## 5. Conclusions

(1) The overall optimization effort is divided into system level optimization and subsystem level optimization. Design variables are divided into global variables for the system level optimization and local variables for the subsystem level optimization. This decomposition strategy makes the aerodynamic/stealthy/structural integrated design be more easily being tackled.

(2) The system level optimization based on surrogate models can reduce computational expense substantially.

(3) The parametric CAD model provides a uniform 3D geometric model for all disciplinary analyses. The analysis models for aerodynamics, RCS, structure, and internal volume are all generated from the 3D parametric CAD model automatically.

(4) The design optimization of each discipline is performed automatically. The aerodynamic/stealthy integrated design optimization code and structural optimization software are easily integrated into the overall process.

(5) The final results obtained from the system optimization can be directly presented as a 3D CAD model in a CATIA environment, which can be used by the downstream design. This feature makes the proposed method be more practical for real world design.

This aerodynamic/stealthy/structural integrated design optimization for UCAV is the most complex problem, which has been solved by our research group. It is found that the overall process of the surrogate-based two-level optimization strategy can be implemented automatically without any difficulty, and quite reasonable results are obtained. The further research will account for more disciplinary effects including propulsion, flight performance, stability, and controls.

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